

# Parameters of type IIP SN 2012A and clumpiness effects

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Received 18 August 2014 / accepted ...

## ABSTRACT

**Context.** The explosion energy and the ejecta mass of a type IIP supernova (SN IIP) derived from hydrodynamic simulations are principal parameters of the explosion theory. However, the number of SNe IIP studied by hydrodynamic modeling is small. Moreover, some doubts exist in regard to the reliability of derived SN IIP parameters.

**Aims.** The well-observed type IIP SN 2012A will be studied via hydrodynamic modeling. Their early spectra will be checked for a presence of the ejecta clumpiness. Other observational effects of clumpiness will be explored.

**Methods.** Supernova parameters are determined by means of the standard hydrodynamic modeling. The early hydrogen H $\alpha$  and H $\beta$  lines are used for the clumpiness diagnostics. The modified hydrodynamic code is employed to study the clumpiness effect in the light curve and expansion kinematics.

**Results.** We found that SN 2012A is the result of the explosion of a red supergiant with the radius of  $715 \pm 100 R_{\odot}$ . The explosion energy is  $(5.25 \pm 0.6) \times 10^{50}$  erg, the ejecta mass is  $13.1 \pm 0.7 M_{\odot}$ , and the total  $^{56}\text{Ni}$  mass is  $0.012 \pm 0.002 M_{\odot}$ . The estimated mass of a progenitor, a main-sequence star, is  $15 \pm 1 M_{\odot}$ . The H $\alpha$  and H $\beta$  lines in early spectra indicate that outer ejecta are clumpy. Hydrodynamic simulations show that the clumpiness modifies the early light curve and increases the maximum velocity of the outer layers.

**Conclusions.** The pre-SN 2012A was a normal red supergiant with the progenitor mass of  $\approx 15 M_{\odot}$ . The outer layers of ejecta indicate the clumpy structure. The clumpiness of the external layers can increase the maximum expansion velocity.

**Key words.** stars: supernovae: individual: SN 2012A – stars: supernovae: general

## 1. Introduction

The general picture of type IIP supernovae (SNe IIP) phenomenon has been understood decades ago (Grassberg et al. 1971; Falk & Arnett 1977; Eastman et al. 1994). The central to this picture is the explosion of a massive red supergiant (RSG) with the energy of the order of  $10^{51}$  erg. Yet the major characteristics – the explosion mechanism and the progenitor mass – remain the matter of debate. The hydrodynamic modeling of the well-observed SNe IIP is the only way to determine the explosion energy and the ejecta mass. The progenitor mass can be obtained via combining the ejecta mass with the mass of neutron star and the estimated mass lost by the stellar wind. In some cases the progenitor mass can be also recovered from the pre-explosion images (Smartt 2009). The application of the hydrodynamic approach requires the well-observed SNe IIP with the reliably defined duration of the light curve plateau. The number of these well-studied events is rather small: at present only eight SNe IIP are studied hydrodynamically (Utrobin & Chugai 2013). Every other well-observed SN IIP therefore is a bonanza for researchers.

The type IIP SN 2012A in the nearby galaxy NGC 3239 became a subject of the detailed observational and theoretical study, including hydrodynamic modeling (Tomasella et al. 2013). The derived parameters seem reasonable except for the small pre-SN radius. Moreover, the hydrodynamic model of Tomasella et al. produces surprisingly low velocity at the photosphere that does not exceed  $3000 \text{ km s}^{-1}$  despite the early H $\alpha$

profile shows the expansion velocity up to  $\sim 10^4 \text{ km s}^{-1}$ ; in addition the Fe II 5169 Å absorption indicates the photospheric velocity of  $5500 \text{ km s}^{-1}$  on day 15 (Tomasella et al. 2013). We therefore find it appropriate to revisit the hydrodynamic modeling of this object.

Another motivation for us to consider SN 2012A originates from the fact that the early ( $t < 20$  d) H $\alpha$  and H $\beta$  lines of type IIP SN 2008in reveal a serious problem (we dub it H $\alpha$ /H $\beta$  problem): the model H $\beta$  absorption turns out too weak compared to the observed absorption, the model H $\alpha$  line being consistent with that observed. It is remarkable that SN 1987A does not show the H $\alpha$ /H $\beta$  problem which prompts a conjecture that this problem is a specific feature of normal SNe IIP originated from the RSG explosion (Utrobin & Chugai 2013). The H $\alpha$ /H $\beta$  problem can be resolved by invoking the clumpy structure of the external ejecta (Chugai & Utrobin 2014). Keeping in mind that SN 2012A in many respects is similar to SN 2008in, it is of great interest to explore whether the H $\alpha$ /H $\beta$  problem arises in the case of SN 2012A as well. If confirmed, the next question should be posed: what are the other observational effects of the proposed ejecta clumpiness? This issue could be explored, for example, by means of one-dimensional hydrodynamic simulations which somehow take into account the clumpy structure of the external ejecta.

Here we perform the hydrodynamic modeling of SN 2012A in order to derive the SN parameters using a standard approach applied earlier to other SNe IIP. We then analyze the early spectra to check whether the H $\alpha$ /H $\beta$  problem arises for SN 2012A

which would indicate the ejecta clumpiness. As we will see this is indeed the case. We also explore the issue of observational effects of the clumpiness on the basis of a modified one-dimensional hydrodynamic code. An additional motivation to study this subject stems from the unsuccessful search for a missing factor responsible for the "mass problem" revealed first for SN 2005cs – the conflict between the high mass obtained from the hydrodynamic modeling (Utrobin & Chugai 2008) and the low mass recovered from archival images (Maund et al. 2005).

## 2. Observational data

The hydrodynamic modeling with the one-group radiation transfer is aimed at reproducing a bolometric light curve and photospheric velocities. For SN 2012A the bolometric light curve is recovered using *UBVR<sub>I</sub>JHK* photometry measured by Tomasella et al. (2013) and corrected for the reddening  $E(B - V) = 0.037^{+0.006}_{-0.008}$  mag adopted by them. We use a black-body spectral fit to calculate the integrated flux with the zero-points reported by Bessell et al. (1998). Following Tomasella et al. (2013), we adopt the distance modulus of  $m - M = 29.96 \pm 0.15$  mag to the nearby galaxy NGC 3239. We use our hydrodynamic model and the calculated *R*-band light curve together with the *R* magnitude at the SN detection (Moore et al. 2012) to fix the explosion epoch at MJD=55930.6. This date is 2.4 days before the explosion moment estimated by Tomasella et al. (2013). Both values however are consistent within the errors. Below we count time from our explosion date. The photospheric velocities for several moments are derived by the modeling of line profiles. From the *H $\alpha$*  and *H $\beta$*  lines we find the velocity values of 9000, 6100, 5400, and 1800 km s<sup>-1</sup> on day 5.5, 12.5, 22.4, and 52.4, respectively. The velocity uncertainty does not exceed  $\pm 100$  km s<sup>-1</sup>.

## 3. Model overview

### 3.1. Standard hydrodynamic model

The numerical modeling of a SN outburst exploits the implicit, Lagrangian, radiation hydrodynamics code CRAB which integrates the spherically-symmetric hydrodynamic equations with a gravity force and radiation transfer equation in the one-group (grey) approximation (Utrobin 2004, 2007). The one-group radiation transfer of the CRAB code is rather accurate approximation for the problems we deal with which is supported by the comparison of the parameters of type IIP SN 1999em recovered by Utrobin (2007) with those obtained by Baklanov et al. (2005) in the framework of their multi-group radiation hydrodynamics code STELLA.

SN 2012A resembles photometrically and spectroscopically the type IIP SN 2008in (Roy et al. 2011) which suggests that parameters of these SNe are close and that in the case of SN 2012A pre-SN is also a RSG star. We will use a non-evolutionary RSG model in the hydrostatic equilibrium for the pre-SN which is exploded by a supersonic piston applied to the bottom of the stellar envelope at the boundary with the  $1.4 M_{\odot}$  central core. The core presumably collapses into a neutron star and remains outside the computational domain.

### 3.2. Modification for clumpy ejecta

In order to explore the effects of the clumpy structure of the outer layers, we modify CRAB code by means of introducing the clumpiness only in the radiation transfer equation leaving the

hydrodynamics intact. However, the clumpiness affects the hydrodynamics implicitly, since the radiative force is modified by the clumpiness via the radiation transfer effects of the clumpy medium.

#### 3.2.1. Radiative transfer in clumpy medium

The radiation transfer in the clumpy medium is treated by using the standard equations in which the absorption (or scattering) coefficient and the emissivity are modified by the inclusion of the clumpiness. We consider a clumpy structure of the outer layers as a medium composed by an ensemble of the dense clumps of a density  $\rho_c$  embedded in a more tenuous interclump medium of a density  $\rho_i$ . With the clump-to-average density contrast  $\chi = \rho_c/\rho$  and the mass fraction of clumps  $\mu$ , the volume filling factor of clumpy component is  $f = \mu\chi^{-1}$ , while the clump and interclump densities are

$$\rho_c = \chi\rho \quad \text{and} \quad \rho_i = \frac{1-\mu}{1-f}\rho. \quad (1)$$

We assume that clumps are uniform spheres of a radius  $a$  which are randomly distributed but do not overlap. The number density of clumps is then

$$n_c = \frac{3f}{4\pi a^3}. \quad (2)$$

A random photon traveling a length  $s$  shares its path between the clumps,  $fs$ , and the interclump medium,  $(1-f)s$  (Kendall & Moran 1963). This suggests that the absorption coefficient in a clumpy medium can be written as a sum

$$k_{tot} = fk_c^{eff} + (1-f)k_i, \quad (3)$$

where  $k_c^{eff}$  is the effective absorption coefficient for the clumps and  $k_i$  is the absorption coefficient for the interclump medium. The absorption coefficient  $fk_c^{eff}$  of the clumpy component enters the element of the optical depth  $d\tau_{cl}$  along the linear displacement  $ds$

$$d\tau_{cl} = fk_c^{eff} ds = \pi a^2 n_c p ds, \quad (4)$$

where  $p$  is the average absorption probability for the photon randomly striking the cloud. After the elementary integration (e.g., Hobson & Padman 1993), the absorption probability reads

$$p = 1 - \frac{1}{2\tau_c^2} + \left( \frac{1}{\tau_c} + \frac{1}{2\tau_c^2} \right) e^{-2\tau_c}, \quad (5)$$

where  $\tau_c = k_c a$  is the clump optical thickness,  $k_c$  is the microscopic absorption coefficient of the clump matter. As expected, the absorption probability  $p = 1$  for the  $\tau_c \gg 1$ , and  $p = 4\tau_c/3$  for  $\tau_c \ll 1$ . Introducing the value  $q(\tau_c) = (3/4\tau_c)p(\tau_c)$  reduces the effective absorption coefficient  $k_c^{eff}$  to

$$k_c^{eff} = k_c q(\tau_c). \quad (6)$$

The emissivity of the clumpy medium is treated in the same way as the absorption coefficient, viz.,

$$\eta_{tot} = f\eta_c^{eff} + (1-f)\eta_i. \quad (7)$$

The emissivity of the clumpy component is

$$f\eta_c^{eff} = \frac{1}{4\pi} n_c L_c, \quad (8)$$

where  $L_c = 4\pi a^2 F$  is the luminosity of a clump and  $F$  is the radiation flux escaping the clump surface. Assuming a homogeneous emissivity  $\eta_c$  across the clump, the emergent intensity in the direction at the angle  $\theta$  to the outward normal is

$$I(\theta) = \int_0^{2\tau_c \cos \theta} \eta_c \exp(-k_c s) ds = \frac{\eta_c}{k_c} [1 - \exp(-2\tau_c \cos \theta)] . \quad (9)$$

Integrating the projection  $I \cos \theta$  over angles gives the flux escaping the spherical clump

$$F = \frac{4}{3} a \eta_c q(\tau_c) . \quad (10)$$

The effective emissivity is thus reduced to

$$\eta_c^{eff} = \eta_c q(\tau_c) . \quad (11)$$

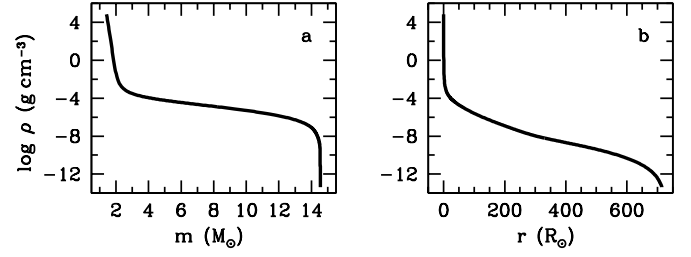
Remarkably, the expressions for the effective absorption coefficient (6) and the effective emissivity (11) look similar; this is an outcome of the optical reversibility. It is worth to note that the function  $q(\tau_c)$  can be interpreted as the escape probability for a photon emitted in a spherical homogeneous clump (Osterbrock 1989).

### 3.2.2. Setting out clumpiness

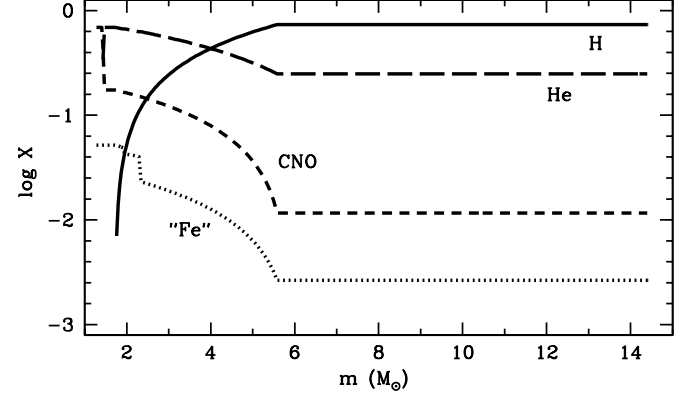
The ejecta clumpiness suggested earlier for SN 2008in (Utrobin & Chugai 2013; Chugai & Utrobin 2014) is presumably generated during the shock wave propagation in the outermost layers of a RSG star which are characterized by the presence of a density inversion and convection (e.g., Paczyński 1969; Maeder 1981; Chiavassa et al. 2011). The mass of these layers depends on the RSG mass and mounts to  $0.01 - 0.2 M_\odot$  for the stellar mass in the range of  $10 - 20 M_\odot$  (Fadeyev 2012). Two mechanisms could be involved in the clumpiness production. The first is related to the shock wave propagation through the density inversion layer which should result in the Rayleigh-Taylor and Richtmyer-Meshkov instabilities. The second mechanism is related to the shock wave propagation through the outer convective zone. The convection velocity in a RSG probed by the macroturbulent velocity attains  $6 - 10 \text{ km s}^{-1}$  (Chiavassa et al. 2011), i.e., comparable to the sound speed. The colliding tangential flows of the neighboring convective cells will produce supersonic collision accompanied by a significant compression. This suggests that the convective zone contains the density perturbations of large amplitude,  $\delta\rho/\rho \sim 1$ . The SN shock wave running through the inhomogeneous convection layer can produce the clumpy post-shock flow with the large density contrast.

We set the inhomogeneous structure of the ejecta by turning on the clumpiness generation when the shock wave reaches the level corresponding to a certain overlying mass, e.g.,  $\approx 0.07 M_\odot$ . The downstream clumpiness parameters  $\mu$  and  $\chi$  are set to grow with the local hydrodynamic time scale from zero to their final values that are limited by the pre-set model values  $\mu_0$  and  $\chi_0$ , respectively. The third parameter, the clump radius  $a$ , is assumed to be the constant fraction of the shell radius  $a/r = 0.016$ ; the value is adopted following the estimate on the basis of the amplitude of flux fluctuations in the  $H\alpha$  line profile of SN 2008in (Chugai & Utrobin 2014).

To facilitate the calculation of temperatures of the clumps and the interclump medium, we assume that they are in a pressure equilibrium. In the optically thick medium the total pressure of gas and radiation is determined by the thermodynamic equilibrium. In contrast, in the optically thin case the pressure equilibrium is predominantly controlled by the gas pressure because



**Fig. 1.** Density distribution as a function of interior mass (Panel **a**) and radius (Panel **b**) for the optimal pre-SN model of SN 2012A. The central core of  $1.4 M_\odot$  is omitted.



**Fig. 2.** The mass fraction of hydrogen (*solid line*), helium (*long dashed line*), CNO elements (*short dashed line*), and Fe-peak elements including radioactive  $^{56}\text{Ni}$  (*dotted line*) in the ejecta of the optimal model.

of a negligible interaction between gas and radiation field and of the same radiation field in both the clumps and the interclump medium. To describe these extreme regimes, we introduce the effective pressure

$$P_{eff}(\rho, T) = \begin{cases} P_g(\rho, T, T_r) & \text{for } \tau \ll 1 , \\ P_g(\rho, T) + \frac{1}{3} a T^4 & \text{for } \tau \gg 1 . \end{cases} \quad (12)$$

The intermediate regimes between the optically thick and thin cases are described by the factor  $\exp(-\tau)$  in the radiation pressure where  $\tau$  is the total optical depth at the certain layer from the outer boundary of the envelope.

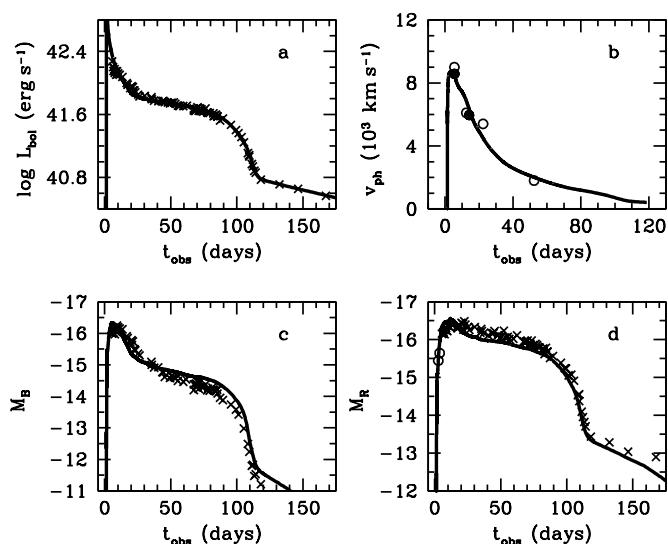
The hydrodynamic code works with a smooth medium described by the density  $\rho$  and the gas temperature  $T$  that specify the effective pressure  $P_{eff}(\rho, T)$ . The pressure equilibrium between the clumps and the interclump matter along with the effective pressure (12) permits us to calculate the gas temperature of the clumps ( $T_c$ ) and interclump matter ( $T_i$ ) from the equalities:

$$P_{eff}(\rho, T) = P_{eff}(\rho_c, T_c) = P_{eff}(\rho_i, T_i) . \quad (13)$$

The temperatures  $T_c$  and  $T_i$  combined with the corresponding densities  $\rho_c$  and  $\rho_i$  (1) and the radiation temperature  $T_r$  are used to calculate the absorption coefficients according to relation (3) and the total emissivity (7) for the clumpy medium which enter the radiation hydrodynamics equations.

## 4. Supernova parameters

The parameters of SN 2012A are determined in a standard way by means of the hydrodynamic simulations of the bolometric



**Fig. 3.** Optimal hydrodynamic model. Panel **a**: the bolometric light curve of the optimal model (*solid line*) overlotted on the bolometric data of SN 2012A (*crosses*) evaluated from the *UBVRIJHK* magnitudes reported by Tomasella et al. (2013). Panel **b**: the calculated photospheric velocity (*solid line*) is compared to the photospheric velocity derived from the  $H\alpha$  and  $H\beta$  lines (*open circles*) (Sect. 2) and from the  $He\ I\ 5876\ \text{\AA}$  line (*filled circles*) (Tomasella et al. 2013). Panels **c** and **d**: the calculated B and R light curves (*solid line*) compared to the observations of SN 2012A (*crosses*) obtained by Tomasella et al. *Two open circles* are the SN detection in R-band (Moore et al. 2012).

light curve and the evolution of the photospheric velocity and their fitting to the observations. The major model parameters are the ejecta mass, the explosion energy, the pre-SN radius, and the total  $^{56}\text{Ni}$  mass. The latter value is fixed by the bolometric luminosity at the radioactive tail and in the case of SN 2012A is equal to  $0.012\ M_{\odot}$ . Additional tuning parameters are the density distribution in the RSG envelope (Fig. 1), the mixing between the helium core and the hydrogen envelope, and the mixing of CNO elements and heavier metals dubbed "Fe" elements which also include the radioactive  $^{56}\text{Ni}$  (Fig. 2). Dependence of the observational properties of a SN IIP outburst on the parameter variations was studied in detail elsewhere (Utrobin 2007). Results of the hydrodynamic modeling are almost independent of the helium-core mass, which is taken in accord with the standard evolutionary models for a single star of a given initial mass. In the case of SN 2012A the helium-core mass is adopted to be  $4\ M_{\odot}$  which corresponds to the non-rotating star with a ZAMS mass of about  $15\ M_{\odot}$  (Hirschi et al. 2004).

Exploring the parameter space results in the optimal model (Fig. 3) with the ejecta mass  $M_{\text{env}} = 13.1\ M_{\odot}$ , the explosion energy  $E = 5.25 \times 10^{50}$  erg, and the pre-SN radius  $R_0 = 715\ R_{\odot}$ . The model reproduces not only the bolometric light curve, but also the B and R-band light curves. The latter plot is especially valuable, because it demonstrates that the earliest photometric points are fitted well and reliably indicate the explosion moment. The model density distribution in the freely expanding envelope on day 50 (Fig. 4) is similar to that of SN 2008in (Utrobin & Chugai 2013) with the outer density power law  $\rho \propto v^{-7.6}$ . The power-law index  $k = -\partial \ln \rho / \partial \ln v$  depends on the density distribution of pre-SN outer layers, which in turn is constrained by the initial luminosity peak. The rule of thumb states that a more luminous and longer initial luminosity peak requires a shallower density distribution in the outer layers, i.e., a lower  $k$  value. It is worth

noting that the modeling of four SNe IIP, namely, SN 2004et (Utrobin & Chugai 2009), SN 2005cs (Utrobin & Chugai 2008), SN 2008in (Utrobin & Chugai 2013), and SN 2012A, results in a similar density gradient with  $k \approx 7.6$  in the outer layers.

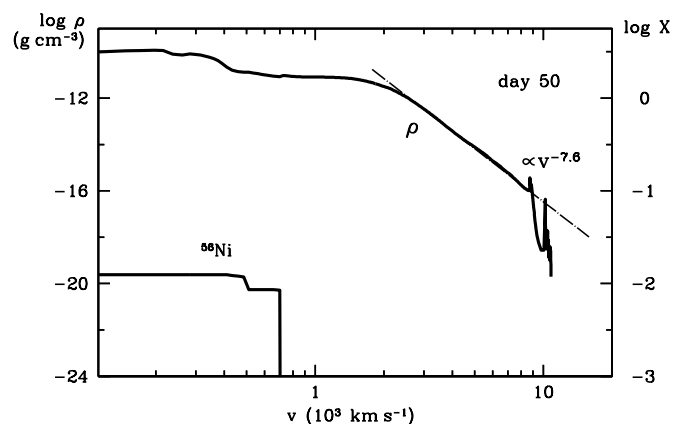
Combining the ejecta mass with the mass of the neutron star gives the pre-SN mass of  $14.5\ M_{\odot}$ . The progenitor ZAMS mass should be larger by the amount lost by the stellar wind. Following the estimate for SN 2003Z with a comparable progenitor mass (Utrobin et al. 2007), we adopt for SN 2012A the lost mass in the range of  $0.2 - 0.8\ M_{\odot}$  in which case the progenitor mass turns out to be  $M = 15.0 \pm 0.3\ M_{\odot}$ .

The parameter errors can be estimated by varying the model parameters around the optimal model. Adopting the uncertainty of 17% in the bolometric luminosity, 4% in the photospheric velocity, and 3% in the plateau duration, we find the errors  $\pm 100\ R_{\odot}$  for the initial radius,  $\pm 0.7\ M_{\odot}$  for the ejecta mass,  $\pm 0.6 \times 10^{50}$  erg for the explosion energy, and  $\pm 0.002\ M_{\odot}$  for the  $^{56}\text{Ni}$  mass. The error of the ejecta mass combined with the uncertainty in the mass loss suggests the progenitor mass error of  $\pm 1\ M_{\odot}$ .

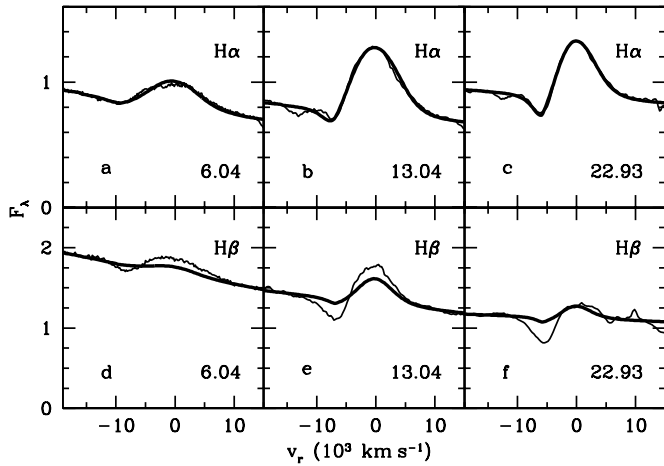
## 5. Clumpiness effects

### 5.1. Evidence from hydrogen lines

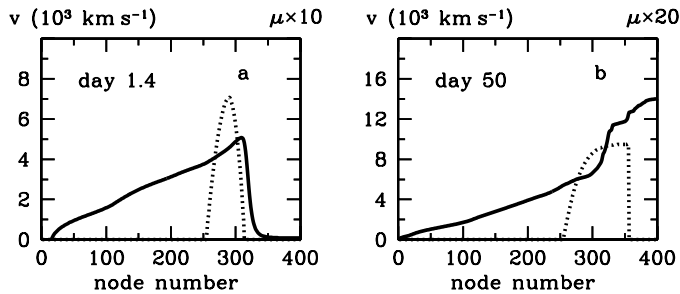
Recently it was found that the  $H\alpha$  and  $H\beta$  lines in the early ( $t \lesssim 20$  d) spectra of SN 2008in cannot be reproduced for the standard spherically-symmetric model (Utrobin & Chugai 2013); the controversy was resolved by assuming the clumpy structure of the outer layers of the ejecta. To check whether the early SN 2012A spectra reveal the similar  $H\alpha/H\beta$  problem, we apply the standard approach to the description of line profiles in an expanding envelope. We consider a freely expanding atmosphere on the top of the photosphere. The  $H\alpha$  and  $H\beta$  line profiles are mainly determined then by the radial distribution of the population of the second hydrogen level,  $n_2(v)$ , and the line source function  $S(v)$ . The latter consists of the scattering and net emission,  $S = W + S_e$ , where  $W$  is the dilution factor and  $S_e$  is the term responsible for the net emission normalized on the photospheric brightness  $I$ . In the framework of this model it is easy to fit the  $H\alpha$  line on day 7, 14, and 23 (Fig. 5). However, the  $H\beta$  absorption component for the best fit function  $n_2(v)$  turns out too weak, i.e., the  $H\beta$  line suggests the larger population of the second level. If we proceed the opposite way, i.e., first fit the  $H\beta$  line and then use the found function  $n_2(v)$  to calculate the  $H\alpha$



**Fig. 4.** The density and the  $^{56}\text{Ni}$  mass fraction as a function of velocity for the optimal model at  $t = 50$  days (*solid lines*). *Dash-dotted line* is the density distribution fit  $\rho \propto v^{-7.6}$ .



**Fig. 5.** The observed H $\alpha$  (upper panels) and H $\beta$  (lower panels) Tomasella et al. (2013) in SN 2012A on day 7, 14, and 23 (*thin line*) compared to the model profiles (*thick line*). The model parameters are adjusted to fit the observed H $\alpha$ . For these models, however, the calculated H $\beta$  is unable to fit the observed profile.

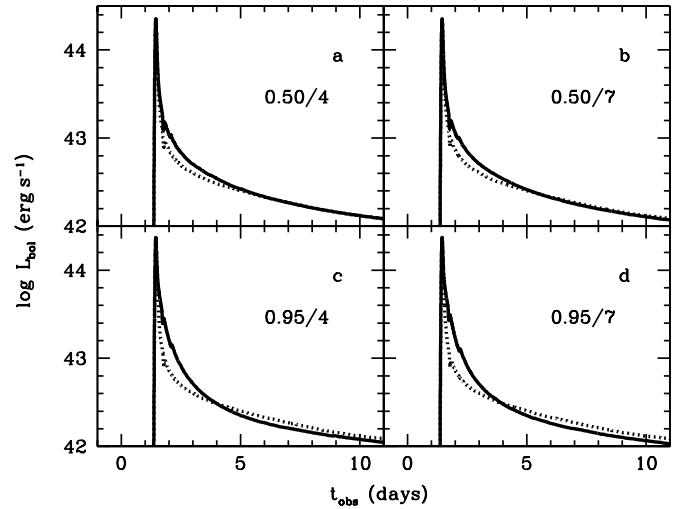


**Fig. 6.** Evolution of velocity and clumping in hydrodynamic model ( $\mu_0 = 0.95$ ,  $\chi_0 = 7$ ) from the moment just before the shock breakout (Panel a) till day 50 (Panel b). *Thick line* is the velocity profile and *dotted line* shows the mass fraction of clumps. Note that the clumpiness is turned off in the outermost layers due to the shock breakout.

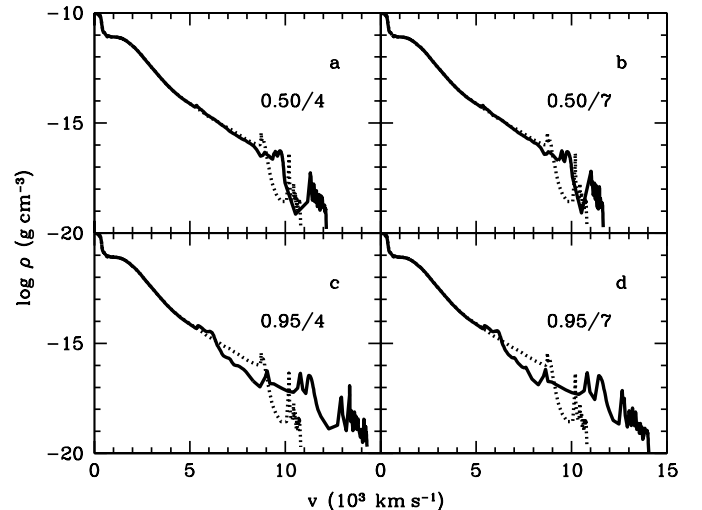
line, we would obtain the unacceptably strong H $\alpha$  absorption. This is exactly the problem we met in the case of SN 2008in.

Following the earlier suggestion for SN 2008in, we assume that the clumpiness of the external layers of the SN 2012A ejecta is responsible for the peculiar H $\beta$  intensity. In this picture the SN atmosphere consists of an ensemble of the dense clouds with the filling factor  $f$  embedded in a rarefied intercloud medium. We managed to fit both the H $\alpha$  and H $\beta$  lines with the filling factor  $f = (v/v_f)^{-2.8}$  for  $v > v_f = 5500$  km s $^{-1}$  and the velocity at the photosphere of 8900, 6200, and 5550 km s $^{-1}$  on day 7, 14, and 23, respectively. This requires a clumpy structure of the outer  $\approx 0.07 M_\odot$  of the ejecta in the optimal hydrodynamic model.

The clumpy model invoked in this case suggests the large clump/interclump ratio of the H $\alpha$  optical depth. On day 14 the H $\alpha$  optical depth in clouds at the fiducial velocity of 8000 km s $^{-1}$  is  $\tau(\text{H}\alpha) = 80$  while in the interclump gas  $\tau(\text{H}\alpha) = 0.5$  at the same velocity, i.e., 160 times lower. Since the density contrast of the clouds unlikely significantly exceeds  $\approx 7$ , the compression ratio in the adiabatic radiation dominated shock, the factor of  $\sim 160$  requires explanation. In this respect we note that in the case when the population rate of the second hydrogen level is dominated by the recombination and the depopulation is controlled by the Ly $\alpha$  escape one expects that the hydrogen concentration  $n_2$  is proportional to  $n^3$ . This means that with the



**Fig. 7.** Dependence of the bolometric luminosity (*thick line*) at the initial peak on the mass fraction of clumps  $\mu_0$  and the density contrast  $\chi_0$  indicated on each panel. The bolometric luminosity peak of the optimal model for the smooth medium is shown by *dotted line*.

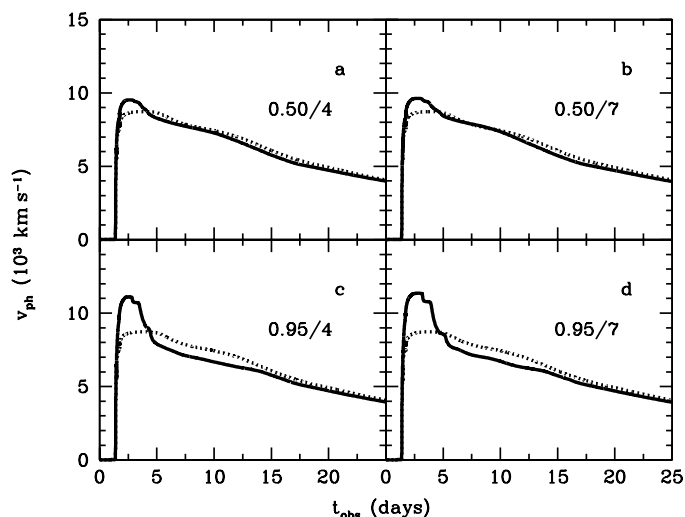


**Fig. 8.** Density as a function of velocity (*thick line*) for the different mass fraction of clumps  $\mu_0$  and density contrast  $\chi_0$  indicated on each panel. Density profile of the optimal model for the smooth medium is shown by *dotted line*.

clump/interclump density ratio of 5 – 6 the required ratio of the H $\alpha$  optical depth in these components can be attained.

## 5.2. Hydrodynamic model with clumpiness

The signatures of the clumpy structure of the ejecta indicated by hydrogen lines pose questions concerning other observational effects of the clumpiness. Following the proposed prescription for the inclusion of the clumpiness into the hydrodynamic simulations (Sect. 3.2), we computed a number of models based on the optimal homogeneous model. The clumpy structure is determined by the adopted mass fraction of clumps  $\mu$  and the density contrast  $\chi$  with the fixed ratio  $a/r = 0.016$ . The clumpiness generation is turned on when the shock wave reaches the external mass coordinate of  $\approx 0.07 M_\odot$ . The evolution of the distributions of  $\mu$  and  $v$  between the shock breakout stage (day 1.4) and



**Fig. 9.** Photospheric velocity evolution (*thick line*) for the different mass fraction of clumps  $\mu_0$  and density contrast  $\chi_0$  indicated on each panel. Photospheric velocity of the optimal model for the smooth medium is shown by *dotted line*.

the free-expansion regime (day 50) is shown in Fig. 6 for the hydrodynamic model with  $\mu_0 = 0.95$  and  $\chi_0 = 7$ . It is noteworthy that in the outermost layers the clumpiness generation is turned off at the shock breakout because of the shock radiative damping. This explains the sharp drop of the  $\mu$  value in the outermost layers clearly seen on day 50.

We show results for the combinations of the mass fraction of the clumps,  $\mu_0 = 0.5$  and  $0.95$ , and the density contrast,  $\chi_0 = 4$  and  $7$ . These  $\chi_0$  values correspond to the adiabatic compression factor for the matter and radiation dominated regimes, respectively. The major effect of the clumpiness is a decrease of the optical depth compared to the homogeneous case. This results in the luminosity enhancement during the first several days (Fig. 7). The effect is larger for the larger  $\mu_0$  and insensitive to the density contrast  $\chi_0$  in agreement with the expression (1) for the density of the interclump medium. As a result of the flux increase the external layers experience a stronger radiative acceleration thus resulting in the larger maximum velocity of the ejecta (Fig. 8). For the mass fraction of the clumps  $\mu_0 = 0.95$  the maximum velocity is about 30% larger compared to the homogeneous model. The density minimum in the range of  $10\,000 - 12\,000 \text{ km s}^{-1}$  separates the main ejecta and the outer  $\sim 10^{-4} M_\odot$  shell formed due to the shock breakout.

It is noteworthy that in addition to the enhanced flux the homogeneous structure of the outermost layers (Fig. 6) is another crucial factor favoring the larger radiative acceleration. Indeed, if the outermost layers were also clumpy, the radiation-matter interaction would not be strong enough to produce the efficient acceleration. To check this argument we computed the hydrodynamic model in which the clumpy structure was set artificially throughout the external layers. This model did not show extra acceleration.

Observationally, velocities of the external ejecta could be probed by the blue wings of the absorption components of the  $H\alpha$ ,  $H\beta$ , and  $\text{He I } 5876 \text{ \AA}$  lines. Unfortunately, the  $H\alpha$  and  $\text{He I } 5876 \text{ \AA}$  absorptions in the first spectrum of SN 2012A on day 7 (Tomasella et al. 2013) are too shallow for confident conclusion. The  $H\beta$  absorption indicates the ejecta velocity up to  $11\,000 - 12\,000 \text{ km s}^{-1}$  which is consistent with the velocity of

the density minimum (Fig. 8) where the absorption intensity significantly drops. We estimate that the  $H\beta$  optical depth in the density minimum is  $\sim 10^{-2}$  on day 7, being beyond the detection limit. Another manifestation of the larger expansion velocity in the clumpy model could be the larger photospheric velocity at the early ( $t < 5 \text{ d}$ ) stage compared to the homogeneous model (Fig. 9). Unfortunately, this cannot be confirmed, because the spectra of SN 2012A are not available at that early stage. As to the later ( $t > 5 \text{ d}$ ) stage, the photospheric velocities of smooth and clumpy models are close each other and consistent with the observational data.

## 6. Discussion and Conclusions

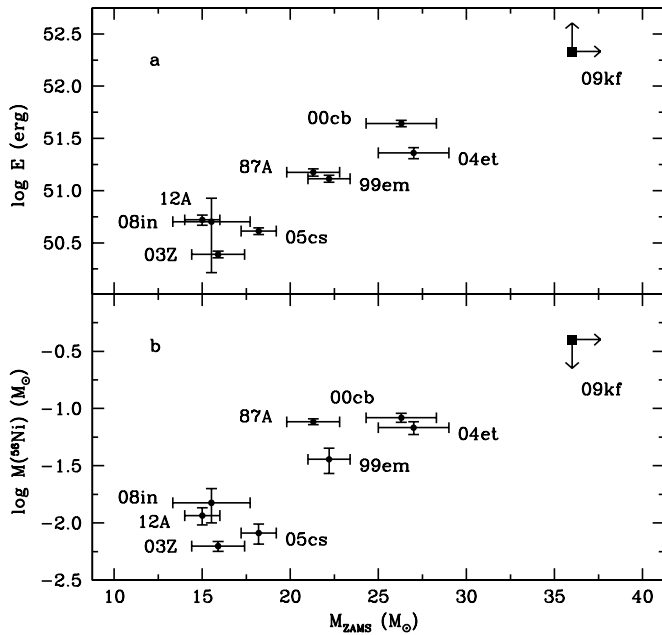
We pursued three goals: to derive the basic parameters of SN 2012A, to probe the clumpiness using the  $H\alpha$  and  $H\beta$  lines, and to explore the possible effects of the ejecta clumpiness. We find the ejecta mass  $M_{\text{env}} = 13.1 \pm 0.7 M_\odot$ , the explosion energy  $E = (5.25 \pm 0.6) \times 10^{50} \text{ erg}$ , the pre-SN radius  $R_0 = 715 \pm 100 R_\odot$ , and the total  $^{56}\text{Ni}$  mass  $M_{\text{Ni}} = 0.012 \pm 0.002 M_\odot$ . We estimate the progenitor mass to be  $15 \pm 1 M_\odot$ . The  $^{56}\text{Ni}$  mass estimate coincides with the value derived by Tomasella et al. (2013). Moreover, the ejecta mass and the explosion energy are close to those obtained by Tomasella et al.. However, our pre-SN radius is three times larger. We rule out significantly smaller radius, because the pre-SN radius is constrained by the initial luminosity peak; it cannot be reproduced in the case of a compact pre-SN star (Tomasella et al. 2013).

With SN 2012A, we have now the parameters of nine SNe IIP which are derived by the unique method of the hydrodynamic simulations (Table 1). Among these objects two events, SN 1987A and SN 2000cb, are produced by the explosion of a blue supergiant and one peculiar event, SN 2009kf, has an anomalously high explosion energy. The ejecta mass of SN 2012A turns out to be the smallest in this sample. In the scatter plots of “explosion energy vs. progenitor mass” and “ $^{56}\text{Ni}$  mass vs. progenitor mass” (Fig. 10), the SN 2012A parameters fall into the bands occupied by other events. In this regard SN 2012A is indeed the normal type IIP event.

The early spectra of SN 2012A show the  $H\alpha/H\beta$  problem – a weak model  $H\beta$  line for the model  $H\alpha$  line consistent with observations – recovered previously for SN 2008in (Utrobin & Chugai 2013; Chugai & Utrobin 2014). The disparity is resolved in the same way as in the case of SN 2008in, i.e., by invoking a clumpy structure of the external ejecta. The ejecta clumpiness is presumably produced during the shock wave propagation in the outer layers of a pre-SN which are associated with the

**Table 1.** Hydrodynamic models of type IIP supernovae.

SN	$R_0$ ( $R_\odot$ )	$M_{\text{env}}$ ( $M_\odot$ )	$E$ ( $10^{51} \text{ erg}$ )	$M_{\text{Ni}}$ ( $10^{-2} M_\odot$ )	$v_{\text{Ni}}^{\text{max}}$ ( $\text{km s}^{-1}$ )	$v_{\text{H}}^{\text{min}}$ ( $\text{km s}^{-1}$ )
1987A	35	18	1.5	7.65	3000	600
1999em	500	19	1.3	3.6	660	700
2000cb	35	22.3	4.4	8.3	8400	440
2003Z	230	14	0.245	0.63	535	360
2004et	1500	22.9	2.3	6.8	1000	300
2005cs	600	15.9	0.41	0.82	610	300
2008in	570	13.6	0.505	1.5	770	490
2009kf	2000	28.1	21.5	40.0	7700	410
2012A	715	13.1	0.525	1.16	710	400



**Fig. 10.** Explosion energy (Panel **a**) and  $^{56}\text{Ni}$  mass (Panel **b**) vs. hydrodynamic progenitor mass for SN 2012A and eight other core-collapse SNe (Utrobin & Chugai 2013). The SN 2012A position on both scatter plots supports the “explosion energy vs. progenitor mass” and “ $^{56}\text{Ni}$  mass vs. progenitor mass” correlations.

density inversion and the vigorous convection in a RSG atmosphere. The mass of the clumpy external layers is estimated to be  $\sim 0.07 M_{\odot}$ . This value is consistent with the mass of RSG layers of  $0.01 - 0.2 M_{\odot}$  above the density inversion for stars in the range of  $10 - 20 M_{\odot}$  (Fadeyev 2012). Although proposed solution of the  $\text{H}\alpha/\text{H}\beta$  problem seems to be reasonable, an independent decisive evidence should be found to confirm this conjecture.

Hydrodynamic simulations with the modified optimal model, which incorporates a clumpiness of the outer  $0.07 M_{\odot}$  layers into the radiation transfer, demonstrate that the most pronounced effect is the increase in the maximum velocity of the ejecta. The physics behind this phenomenon is the clumpiness in the outer layers with the outermost smooth layer of low mass. The clumpiness favors the larger luminosity which results in the efficient radiative acceleration of the outer layers.

The effect of larger velocity in the clumpy outer ejecta is highly remarkable, because the low photospheric velocity at very early phase is a specific feature of hydrodynamic model of SNe IIP with the low pre-SN mass (Utrobin & Chugai 2008). That was the reason why the ejecta mass and the explosion energy of the model have been pushed up in order to account for the observed large expansion velocity of the outer layers. The increase of velocities of the outer ejecta in the clumpy model compared to the smooth one opens an interesting possibility to produce a hydrodynamic model of SNe IIP with the lower pre-SN mass. One can hope thus to resolve the mass problem, i.e., the conflict between the high hydrodynamic mass for SNe IIP and the low mass based on the archival pre-explosion images. The problem was first uncovered for SN 2005cs (Utrobin & Chugai 2008) when we compared the progenitor mass of  $17 - 19 M_{\odot}$  obtained from the hydrodynamic modeling with the  $7 - 12 M_{\odot}$  ZAMS mass recovered by Maund et al. (2005) from the archival images. This disparity has emerged in several other cases as well. For SN 2012A the hydrodynamic mass is slightly larger than the mass recovered from the pre-explosion image although they are

consistent within errors (Tomasella et al. 2013). The possibility to resolve the mass problem for SNe IIP by invoking the ejecta clumpiness is promising and requires a separate study.

**Acknowledgements.** We thank Lina Tomasella for kindly sending us spectra of SN 2012A. V.P.U. is grateful to Wolfgang Hillebrandt, Ewald Müller, and Hans-Thomas Janka for hospitality during stay at the MPA. V.P.U. is supported by Russian Scientific Foundation grant 14-12-00203.

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